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博　士　学　位　论　文

九龙江流域和江东库区浮游植物群落结构的演替特征及其影响因子研究

Dynamics of phytoplankton community structure and its controlling factors in Jiulong River Watersheds and Jiangdong Reservoir, Fujian

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摘　要

本文通过现场大面调查，重点测站高频率、长期的跟踪监测等实验手段，以九龙江流域西溪和北溪作为主要研究区域，以九龙江北溪江东库区为重点监测水域，利用显微镜镜检并结合光合色素高效液相色谱分离分析法，以及利用浮游植物功能类群的分类方法对上述区域浮游植物组成及类群空间分布、季节变化及影响因子开展了系统的研究。此外，成功分离培养了 2009 年甲藻水华原因种--佩氏拟多甲藻 (*Peridiniopsis penardii*)，并初步研究了不同 N/P 比值对其生长的影响。取得如下主要结果：

九龙江北溪不同水文期浮游植物群落结构及其影响因子

分别于 2011 年枯水期 (2 月)、丰水期 (5 月) 和平水期 (10 月)，系统调查研究了福建九龙江北溪浮游植物群落组成、丰度的分布特征及其与环境因子的关系。共鉴定浮游植物 107 种，隶属于 7 门 64 属。不同水文期浮游植物主要优势种类不同，枯水期为马索隐藻 (*Cryptomonas marssoni*)、梅尼小环藻 (*Cyclotella meneghiniana*) 和颗粒直链藻 (*Aulacoseira granulata*)，丰水期为四尾栅藻 (*Scenedesmus quadricauda*)、四角十字藻 (*Crucigenia tetrapedia*) 和颗粒直链藻极狭变种 (*Aulacoseira granulata* var. *angustissima*)，平水期则演替为微小平裂藻 (*Merismopedia tenuissima*)。不同水文期浮游植物丰度变化明显，其平均值依次为枯水期 (154.77×10^4 cells L^{-1}) >平水期 (76.40×10^4 cells L^{-1}) > 丰水期 (45.40×10^4 cells L^{-1})。相关分析显示，3 个水文期浮游植物细胞丰度与硝氮呈显著正相关 ($p<0.01$)；丰水期浮游植物丰度与温度呈显著正相关 ($p<0.01$)。典范对应分析 (CCA) 表明，水体温度是影响该水域浮游植物分布格局的重要因子，此外，硝氮、氨氮和溶解态活性磷浓度也对浮游植物的分布有较大影响。CCA 排序图较好地显示了浮游植物物种分布和环境因子之间的关系。

九龙江西溪不同水文期浮游植物群落结构及其影响因子：

于 2011 年枯水期 (2 月)、丰水期 (5 月) 和平水期 (10 月)，系统调查研究了福建九龙江西溪浮游植物群落组成、丰度的分布特征及其与环境因子的关系。3 个水文期共鉴定浮游植物 98 种，隶属于 7 门 62 属。不同水文期浮游植物主要优势种类不同，枯水期为颗粒直链藻和四尾栅藻，丰水期为马索隐藻、啮蚀隐藻

(*Cryptomonas erosa*) 和颗粒直链藻极狭变种，平水期则演替为微小平裂藻。不同水文期浮游植物平均丰度值依次为枯水期 (177.44×10^4 cells L^{-1}) >丰水期 (88.29×10^4 cells L^{-1}) >平水期 (87.28×10^4 cells L^{-1})。浮游植物生物量 (Chl *a*) 在 0.48-32.56 μg L^{-1} 之间波动。相关性分析表明，西溪丰水期浮游植物丰度、Chl *a* 与氨氮显著正相关 ($p<0.05$)，而平水期浮游植物丰度、Chl *a* 与水温和氨氮显著正相关 ($p<0.01$)。典范对应分析(CCA) 表明，水体温度同样是影响该水域浮游植物分布格局的重要因子，此外，溶解态活性磷浓度也对浮游植物的分布有较大影响。

九龙江江东库区浮游植物的结构特征及其影响因子

2010 年 1 月至 2012 年 2 月，通过两年的高频率的表层采样工作 (每周一次或 2 周一次)，详细阐述了福建九龙江北溪江东水库浮游植物的演替及其影响因子。研究期间，共鉴定浮游植物 123 种，隶属于 7 门 74 属，浮游植物群落组成以绿藻、硅藻、隐藻和蓝藻为主，甲藻和裸藻也是库区常见的藻类。浮游植物群落演替由隐藻、硅藻向绿藻、蓝藻演替。从功能类群上看，功能类群 P、D、C、Y、J、G、F、S1 和 L_O 是库区主要的浮游植物类群，其中功能类群 P、J、Y 常年出现，成为浮游植物组成的主要贡献者。江东库区冬季 (尤其在 12 月和 1 月)，水体稳定，光照强度低，Y (马索隐藻、啮蚀隐藻)、X2 [衣藻 (*Chlamydomonas* sp.)] 和 X1 [狭形纤维藻 (*Ankistrodesmus angustus*)] 是优势的功能类群。早春时期 (2 月底-3 月)，库区水体扰动增强，功能类群 C [梅尼小环藻、美丽星杆藻 (*Asterionella Formosa*)] 和 P (颗粒直链藻、颗粒直链极狭变种) 成为优势。4 月，库区水体的透明度增加，温度升高，功能类群 J [四尾栅藻、二角盘星藻 (*Pediastrum duplex*)]、G [实球藻 (*Pandorina* sp.)、空球藻 (*Eudorina elegans*)] 的优势增加。5、6 月，库区的扰动较大，功能类群 D [放射针杆藻 (*Synedra actinastroides*)]、N [乳突顶接鼓藻 (*Spondylosium papillosum*)]、MP [间断羽纹藻 (*Pinnularia interrupta*)] 和 T_B [变异直链藻 (*Aulacoseira varians*)] 的优势增加。7、8 月，库区温度较高，营养浓度较低，功能类群 F [网球藻 (*Dictyosphaerium ehrenbergianum*)]、L_O [微小平裂 (*Merismopedia tenuissima*) 和多甲藻 (*Peridinium* sp.)]、S1 [伪鱼腥藻 (*Pseudanabaena mucicola*)]和 S_N [尖头藻 (*Raphidiopsis* sp.)、拉氏拟柱孢藻 (*Cylindrospermopsis raciborskii*)] 的优势增加。

9、10 月，库区水体的营养盐浓度回升，温度较高。水体的功能类群 J、G 的优势重新出现，此时，功能类群 S_N (尖头藻) 的优势度也增加。进入 12 月后，水温降低，光照强度减弱，功能类群 Y 重新成为优势类群。CCA 分析中，硅藻的特征色素 Fucoxanthin 位于排序轴的右上方，表明江东库区硅藻受流量的影响较大；而蓝藻的特征色素 Zeaxanthin 与温度显著相关，温度是蓝藻演替的主要影响因素。CCA 的结果表明水温、流量和透明度是影响浮游植物动态的主要环境变量，浮游植物群落动态可能通过水体流量、光照、水温和营养盐结构来解释。

不同 N/P 比值对佩氏拟多甲藻生长的影响

成功分离培养了 2009 年甲藻水华原因种--佩氏拟多甲藻，并初步研究了不同 N/P 比值对其生长的影响，结果显示，不同 N/P 比值（起始值分别为 8:1、16:1、32:1、64:1）条件下，佩氏拟多甲藻的比生长速率变化范围为 0.09-0.69 d^{-1}。不同 N/P 比值实验组中佩氏拟多甲藻的比生长率与 SRP 存在显著正相关 (p<0.05)；与 N/P 存在显著负相关 (p<0.05)。通过对佩氏拟多甲藻在不同 N/P 比值的体系中的培养，我们发现四组不同 N/P 的培养体系中，佩氏拟多甲藻的比生长率与 N/P 比值之间存在显著负相关，与 2009 年水华期间的监测及 2010-2012 年的现场检测的结果相一致。

基于浮游植物优势种及浮游植物生物量的九龙江江东库区水质评价:

从浮游植物优势种上看，九龙江江东库区常见的藻类为颗粒直链藻、颗粒直链藻极狭变种、梅尼小环藻、马索隐藻、四尾栅藻和微小平裂藻，它们多数是中污带的指示生物。金藻一般被认为是贫营养条件的指示，研究期间，金藻仅在库区中零星出现，表明水库的富营养状态。另外，浮游植物生物量也可作为其生活水环境状态的评估标准之一。2010-2012 年监测期间，江东库区的浮游植物生物量 (湿重) 的范围在 0.453-18.922 mg L^{-1} 之间变化。从浮游植物生物量的角度上看，监测期间江东库区水体环境存在程度差 “bad” 的评估状态，也进一步证实了库区水质已经受到一定程度的污染。

关键词： 浮游植物类群组成，水华，光合色素，浮游植物功能类群，环境因子，典范对应分析 (CCA)，九龙江，江东库区。

Abstract

Phytoplankton blooms are becoming more prevalent throughout Jiulong River Watershed, especially in Jiangdong Reservoir over recent years, which are responsible for causing human health problems as Jiulong River is the main source of drinking water supply for Xiamen (Amoy) City, Fujian Province. It is essential to collect data of general structure of phytoplankton community, e.g. its composition, abundance and seasonal dynamics, for a better understanding of how phytoplankton interacts with environmental factors. Following this lead, phytoplankton abundance, spatial and temporal variations of phytoplankton community structure were recorded by employing the use of microscopy and high performance liquid chromatography (HPLC) in Jiulong River watershed, Fujian Province, from January 2010 to February 2012. Furthermore, *Peridiniopsis penardii*, a dinoflagellate bloom species discovered in Beixi of Jiulong River during January, 2009, was successfully isolated and clonal culture was set up in lab, which allowed us to perform experiments and make a comparison of its growth rate under different N/P ratios. The main findings in present investigation were as follows:

Phytoplankton composition and its relationship with environmental factors in Beixi, Jiulong River, Fujian

Phytoplankton composition and its relationships with environmental factors were studied at 15 stations in Beixi of Jiulong River, Fujian Province, in February (dry season), May (wet season) and October 2011 (normal season), respectively. A total of 107 phytoplankton species were identified, belonging to 64 genera and 7 phyla. The dominant species changed with seasons. *Cryptomonas marssoni*, *Cyclotella meneghiniana* and *Aulacoseira granulata* dominated in the dry season, while *Scenedesmus quadricauda*, *Crucigenia tetrapedia* and *Aulacoseira granulata* var. *angustissima* dominated in the wet season, and *Merismopedia tenuissima* dominated in the normal season. The abundance of phytoplanktonwas the highest in the dry season (averaged 154.77×10^4 cells L^{-1}), followed by the normal season (76.40×10^4

cells L^{-1}) and the wet season (45.40×10^4 cells L^{-1}). The abundance in all three hydrogeological seasons was significantly positively correlated with nitrate concentration (p<0.01), while that in wet season was significantly positively correlated with water temperature (p<0.01). Canonical correspondence analysis(CCA) showed that water temperature was the most important factor affecting the phytoplankton community. Besides these, nitrate, ammonium and soluble reactive phosphorus were also important for phytoplankton community composition. The CCA ordination plots could well display the phytoplankton community structure and its relationships with environmental factors.

Phytoplankton composition and its relationship with environmental factors in Xixi, Jiulong River, Fujian

An investigation was conducted on the phytoplankton's community composition, abundance, and their relations with environmental factors in Xixi of Jiulong River, Fujian Province, in February (dry season), May (wet season) and October 2011 (normal season), respectively. A total of 98 phytoplankton species were identified, belonging to 62 genera and 7 phyla. The dominant species changed with seasons. *Aulacoseira granulata* and *Scenedesmus quadricauda* dominated in the dry season, while *Cryptomonas marssoni*, *Cryptomonas erosa* and *Aulacoseira granulata* var. *angustissima* dominated in the wet season, and *Merismopedia tenuissima* dominated in the normal season. The abundance of phytoplankton was the highest in the dry season (averaged 177.44×10^4 cells L^{-1}), followed by the wet season (88.29×10^4 cells L^{-1}) and the normal season (87.28×10^4 cells L^{-1}). The abundance and Chl *a* in the wet season was significantly positively correlated with ammonium concentration (p<0.05), while there was significantly positively correlated with water temperature and ammonium concentration in the normal season (p<0.01). Canonical correspondence analysis (CCA) showed that water temperature also was the most important factor affecting the phytoplanktoncommunity. The CCA ordination plots could well display the phytoplanktoncommunity structure and its relationships with environmental factors.

Dynamics of phytoplankton functional groups and its controlling factors in Jiangdong Reservoir of Jiulong River, Fujian:

We sampled phytoplankton and environmental parameters weekly or biweekly from January 2010 to February 2012 in the reservoir. Totally, 123 species of phytoplankton were identified which belonged to 74 genera and 7 phyla. Five phyla, Chlorophyta, Bacillariophyta, Cryptophyta, Cyanophyta, and Dinophyta were dominant in phytoplankton community. In addition, Dinophyta biomass was occasionally high during winter and summer. The pattern succession of the phytoplankton community was from Cryptophyta-Bacillariophyta dominance to that of Chlorophyta-Cyanophyta. The winter phase (especially December and January) is characterized by dominance of functional group Y, X1 and X2, including dominant species *Cryptomonas marssonii* and *Cryptomonas erosa* in the former, *Ankistrodesmus angustus* in X1, and *Chlamydomonas* sp. in the latter. Functional groups C (*Cyclotella meneghiniana* and *Asterionella formosa*) and P (*Aulacoseira granulata* and *Aulacoseira granulata* var. *angustissima*) dominated in early spring phase (from later February to March) under condition of high turbulence and low irradiance. The dominance of Functional groups J (*Scenedesmus quadricauda* and *Pediastrum duplex*) and G (*Pandorina* sp. and *Eudorina elegans*) increased in April under the condition of low turbulence and high temperature. Functional groups D (*Synedra actinastroides*), MP (*Pinnularia interrupta*) and T_B (*Aulacoseira varians*) increased between May and June with high turbulence. Functional groups F (*Dictyosphaerium ehrenbergianum*), L_O (*Merismopedia tenuissima* and *Peridinium* sp.), S1 (*Pseudanabaena mucicola*) and S_N (*Raphidiopsis* sp. and *Cylindrospermopsis raciborskii*) increased dominance in summer is characterized by high temperature and low nutritions. Functional groups J (*Scenedesmus quadricauda* and *Pediastrum duplex*) and G (*Pandorina* sp. and *Eudorina elegans*) became dominant groups again between September and October with slowly increased nutrients. Functional group Y got the upper hand again in December with low temperature and low irradiance. In the present study, CCA analysis suggested that Fucoxanthin (a diagnostic pigment for Bacillariophyta) was best associated with discharge. It showed that Bacillariophyta

was greatly influenced by the discharge in Jiangdong Reservoir. Moreover, Zeaxanthin (a diagnostic pigment for Cyanophyta) was significant positive correlation with temperature. The result indicated that the growth of phytoplankton community was affected by river discharge, irradiance, water temperature, and nutrient concentrations.

Effect of different N/P ratios on the growth of *Peridiniopsis penardii*:

The effects of different N/P ratios (N:P=8:1, 16:1, 32:1, 64:1 at the beginning of the test) on the growth of *Peridiniopsis penardii*, a dinoflagellate bloom species in Beixi of Jiulong River during January, 2009, were studied in laboratory batch cultures, which were conducted based on environmental condition during algal bloom. The results indicated that the specific growth rate ranged between 0.09-0.69 d^{-1}. Significant positive correlation was observed between the specific growth rate and phosphate (p<0.05, r=0.329). while there was significant negative correlation was also observed between the specific growth rate and N/P ratio (p<0.01, r=-0.308). It is consistent with the observation results of bloom field monitoring in 2009, and long-term monitoring in Jiangdong Reservoir during 2010-2012.

Ecological status assessment by phytoplankton biomass and dominant species in Jiangdong Reservoir, Jiulong River, Fujian

Based on indicators of the dominant species of *Aulacoseira granulata*, *Scenedesmus quadricauda*, *Cryptomonas marssoni*, *Aulacoseira granulata* var. *angustissima*, *Merismopedia tenuissima* and *Cyclotella meneghiniana* meso-eutrophication or eutrophication was verified in Jiangdong Reservoir, Jiulong River, Fujian. Chrysophytes are generally considered to indicator of oligotrophic condition, their presence was sporadic, which confirms the eutrophic status of Jiangdong Reservoir. Furthermore, phytoplankton biomass could be used to appraise water quality.The phytoplankton biomass fluctuated between 0.453 and 18.928 mg L^{-1} in Jiangdong Reservoir, during 2010-2012. More than half of the monitoring period, in terms of phytoplankton biomass water quality was tolerable/bad status, which also confirms the eutrophic status of Jiangdong Reservoir.

Key words: Phytoplankton composition, Algal bloom, Photosynthetic pigments, phytoplankton functional groups, environmental factors, Jiulong River, Jiangdong Reservoir.